HOSTED BY
ELSEVIER
CrossMark
Available online at www.sciencedirect.com
ScienceDirect
Journal of Magnesium and Alloys 2 (2014) 203–207
www.elsevier.com/journals/journal-of-magnesium-and-alloys/2213-9567

Full length article

On the cold rolling of AZ31 Mg alloy after Equal Channel Angular Pressing

Seyed Mohammad Arab*, Abbas Akbarzadeh

Department of Materials Science and Engineering, Sharif University of Technology, Azadi Ave., P.O. Box 11155-9466, Tehran, Iran

Received 27 February 2014; revised 13 June 2014June 13, 2014; accepted 11 August 2014
Available online 18 October 2014

Abstract

Among the various Severe Plastic Deformation (SPD) processes, Equal Channel Angular Pressing (ECAP) is one of the most applicable one which improves strength and ductility due to grain refinement and suitable texture development. In this study, cold rolling were carried out on the 4 pass ECAPed (in route A and C) strip shaped specimens of AZ31 magnesium alloy to investigate the ECAP effects on the roll-ability. Results showed that reduction in area which can be concerned as an index for roll-ability increased after ECAP. It was also seen that ECAP in route C enhanced roll-ability more than route A.

Keywords: Equal Channel Angular Pressing (ECAP); AZ31 Mg alloy; Roll-ability

1. Introduction

Between all microstructural parameters of crystalline metallic material, grain size has important influences on the physical and mechanical properties. Hall–Petch relationship correlates the strength to grain size as below,

$$\sigma_y = \sigma_\circ + k_y d^{-\frac{1}{2}} \tag{1}$$

where the $\sigma_\circ$ is the friction stress, d is the average grain size, σ_y is the yield stress and k_y is constant [1]. Recently, severe plastic deformation (SPD) processes such as Equal Channel Angular Pressing (ECAP) [2], Accumulative roll bonding [3,4], Cyclic Extrusion Compression (CEC) [5], High Pressure Torsion (HPT) [6] and Friction Stir Processing (FSP) [7] has been developed to improve the microstructure and mechanical properties through grain refinement and a proper texture development. ECAP has had more interests of all SPD processes since it can be applied to wide range of materials, repeated for several passes to impose higher strains and able to get industrialized [8]. ECAP has generally carried out on the bars or rods with circular or square cross section; therefore, there is the need for secondary rolling process in order to make usable flat specimens.

One of the newest areas of recent researches to solve this problem is ECAP of flat samples such as strips, sheets and rectangular billets [9]. Magnesium alloys have high strength to weight ratio, so they are used widely in the automotive, aerospace and electrical industries, although, poor workability at ambient temperature due to rare appropriate slip systems in HCP materials has made them difficult to form plastically [10]. ECAP, in fact develops a non-basal texture by crystallographic plane rotations which activates more slip systems and improves low temperature ductility in addition to enhance the strength by grain refinement in Mg alloys [11–13]. As known, rolling can change the initial grain orientation of workpiece by crystallographic plane orientation and rotational recrystallization. On the other hand, there is a suitable initial orientation to achieve higher plastic deformation orders [14,20]. In this study, a new die was designed in order to process the strip shaped samples, then a proper rotated basal

* Corresponding author.
E-mail address: syedmohammadarab@yahoo.com (S.M. Arab).
Peer review under responsibility of National Engineering Research Center for Magnesium Alloys of China, Chongqing University.

http://dx.doi.org/10.1016/j.jma.2014.08.003.

texture was developed by ECAP trough two different routes. After that the effect of texture development and grain refinement on the room temperature workability of ECAPed flat samples was investigated by tensile test and cold rolling tests. The non basal orientation development was observed by XRD examinations. It was understood that ECAP played a key role on low temperature workability of magnesium alloy.

2. Experiments

Based on the author's recent study [16], ECAP has carried out on the strip shaped specimens in the route C (180° rotation about the longitudinal axis between passes) and A (no rotation) for 4 passes at 200 °C in order to achieve to an appropriate refined grain structure and a suitable texture. Fig. 1 illustrates the schematic of novel die which has designed for this study. Later on, tensile tests and X-ray Diffraction (XRD) examinations were used to investigate mechanical properties and basal plane orientation development. A picric acid (4.2 gr) − acetic acid (10 ml) − distilled water (10 ml) − ethanol (70 ml) solution was used for etching the samples. Then optical microscopy and CLEMEX commercial software were used to grain size measurement and its distribution. After ECAP, specimen cold rolled at room temperature until side cracks were appeared. Side crack appearance was taken as a criterion to stop the rolling.

3. Results and discussion

The microstructure of as received samples is shown in Fig. 2. The bimodal structure which contains coarse and fine grain can be seen in Fig. 2 clearly. Bimodal structure can be due to insufficient slip systems of HCP structures which lead to different deformation levels of initial grains [15].

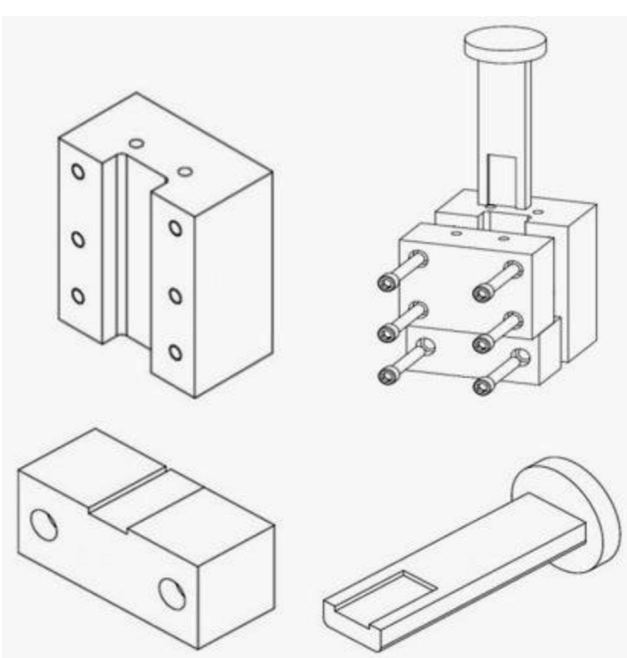

Fig. 1. Schematic of die designed for strip shaped specimens ECAP.

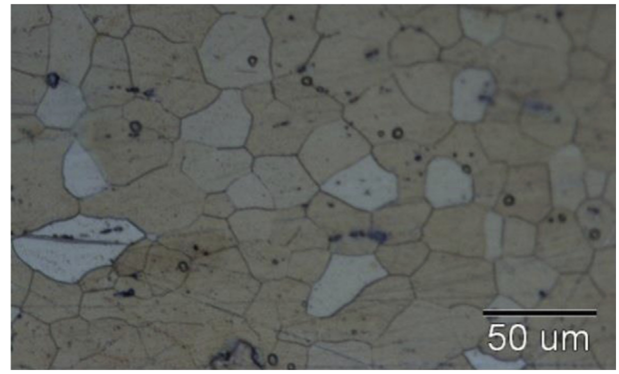

Fig. 2. Bimodal microstructure of as received sample.

Fig. 3 illustrates microstructure of 2 and 4 passes ECAPed specimen at 200 °C through the route C and A. The mean grain size in the initial sample was 38.9 μm (Fig. 2). It should be noted that graphical sketches were used to measure the grain size and its distribution.

It's seen that mean grain size was reduced and distributed more homogenous after 4 passes ECAP which is confirmed by other investigations [12,13,16]. ECAP in route C has given finer grains, because rotation between passes activates more slip systems [17,18] (Fig. 4). The bimodal grain structure contains coarse grain surrounded by recrystalized fine grains was also seen. Investigations showed that grain refinement gets slow after first passes. It can be related to Grain Boundary Sliding (GBS) activation after first passes which depreciates strain energy due to plastic deformation and reduces dynamic recrystallization motivation force. GBS mechanism can decline stress slopes in the coarse grains, so rotational dynamic recrystalization rate decreases in regions near to grain boundaries [20]. Related histograms illustrated normal distribution of the grain [16].

The fine recrystallized grains from initial passes remained unchanged and coarse grains refined through the further passes, however after 4 passes, there were some coarse grains surrounded by fine grains. The wide distribution of the grain size [16] also represented this bimodal microstructure. Basically, observation indicated that main part of grain refinement and microstructure homogenization took place during two first passes and then descended. It can be concluded that by refining the grains in the primary passes, grain boundary sliding mechanism was activated and some portions of strain energy were depreciated by this mechanism. So, the stored strain energy in some grains was reduced. As a result, dynamic recrystallization driving force was diminished and microstructure refining process slowed down. On the other hand, grain boundary sliding activation led to a decrease in stress and strain profile slope in the coarse grains. So the continuous dynamic recrystallization slowed down due to rotation of near to grain surface regions [20].

Fig. 5 illustrates as received and cold rolled 4 pass ECAPed specimens. The rolling was conducted at room temperature.

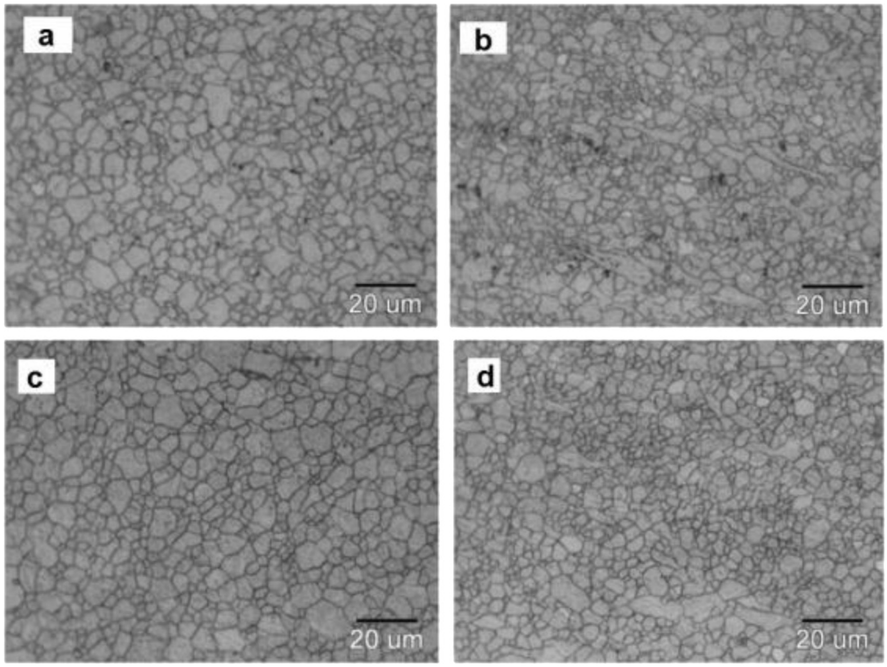

Fig. 3. Microstructure of ECAPed specimens at 200 °C in route A and a) pass 2; b) pass 4; route C and c) pass 2; d) pass 4.

The angular velocity was 30 rpm and reduction in area was 3% per pass. The final reduction of each sample is given in Table 1. The as received specimen cracked after 4 pass rolling.

Tensile test results showed both ductility and tensile stress enhancement after ECAP (Fig. 6). The yield strength decreased and elongation decreased. Unlike the grain refinement, reduction of yield strength and enhancement of elongation can be related to a change in the plastic deformation mechanism and number of slip systems. As mentioned, severe plastic deformation leads to grain refinement and activation of some other plastic deformation mechanisms like grain boundary sliding [20,21]. Other reason for higher roll-ability of ECAPed samples is non *Basal*||*ND* texture formation due to ECAP (Fig. 7). Basal texture is not suitable for tensile test and further rolling in Mg and its alloys [18,19]. Rolling causes to restoration of *Basal*||*ND* texture and as it gets back slower, HCP alloys can tolerates more plastic deformation. So, small reductions per pass, more grain refinement and intensive non basal texture cause to more ductility before cracking. Route C imposes more intensive non basal texture and so leads to more tolerable reduction in rolling. It should be noted that even a perfect non basal texture can't prepare 5 independent slip

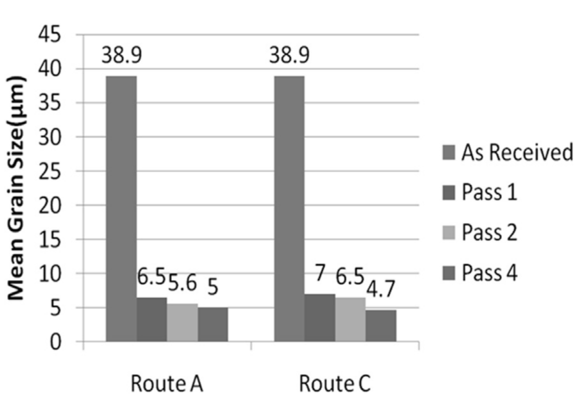

Fig. 4. Mean grain size of ECAPed specimens in route A and C.

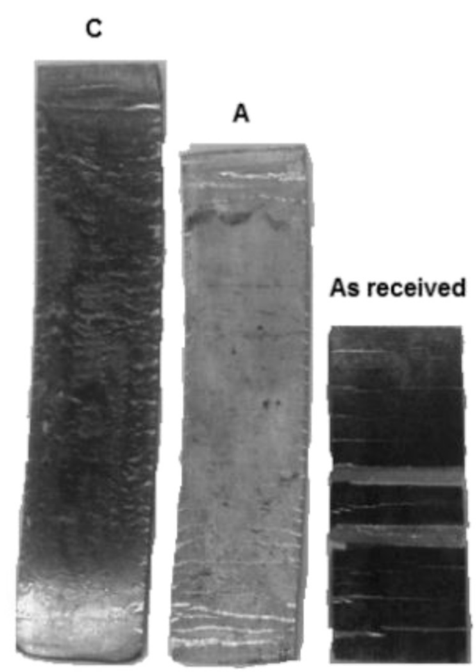

Fig. 5. As received, ECAPed at 200 °C in route A and C specimens which is cold rolled at room temperature.

Table 1
Cold rolling reduction before side cracking in as received and ECAPed specimens.

Route	Pass	Reduction before side cracking
–	0	0.09
A	4	0.37
C	4	0.49

systems and twinning will occurs (Fig. 8). Twinning can change the Schmidt-factor of non basal slip systems and make them more active [15,22].

4. Conclusion

In this study, pass number and ECAP route effects were investigated on the microstructure, mechanical properties and further cold roll-ability of striped shaped AZ31 mg alloy. It was seen that:

1 -Increase in pass numbers (strain) reduces grain size and gives a more homogenous microstructure.
2 -Rotational dynamic recystallization is dominant grain refinement mechanism in magnesium alloys.
3 -Ductility enhancement after ECAP can be related to refined structure and non basal texture development.
4 -More intensive non basal texture and refined grain structure leads to activation of more slip systems and other plastic deformation mechanism like GBS and so more reduction during cold rolling at room temperature.

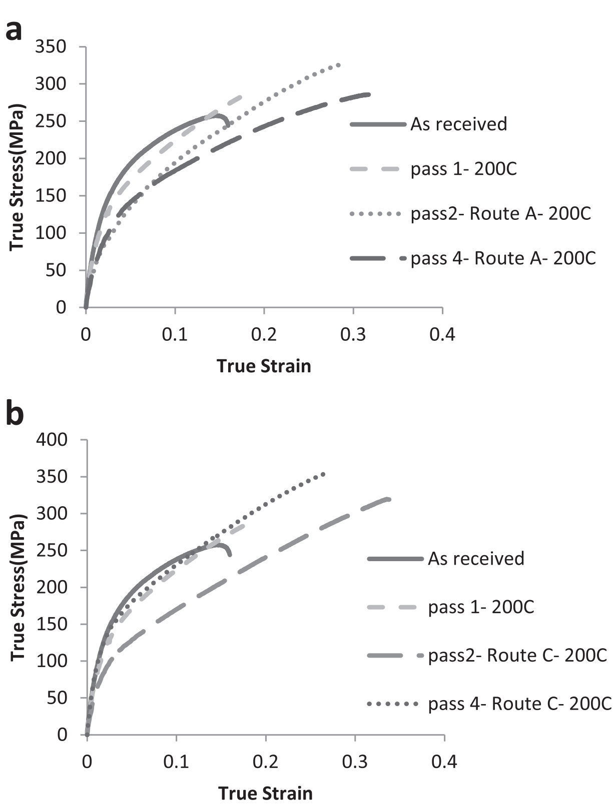

Fig. 6. Tensile test after ECAP in route a) C and b) A.

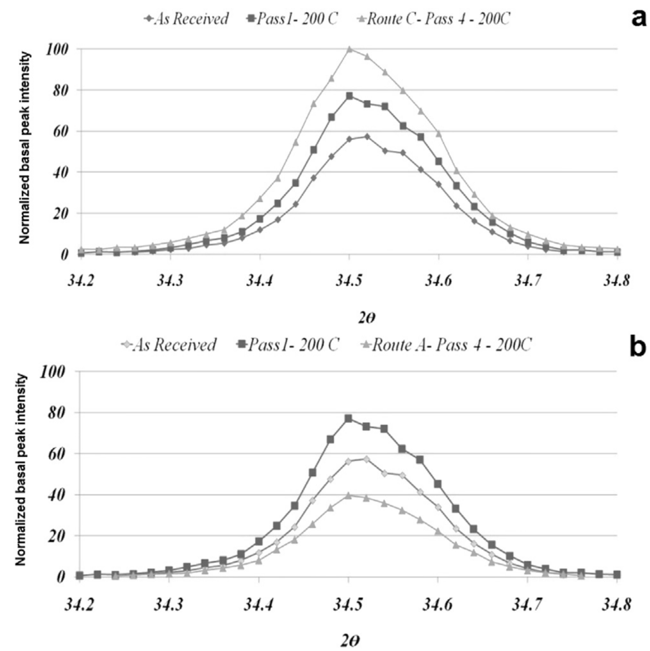

Fig. 7. Basal plane peak intensity changes during ECAP in route A and C at 200 °C.

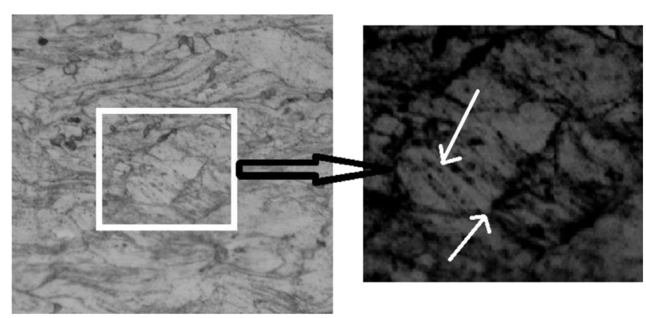

Fig. 8. Twinning appearance after cold rolling of ECAPed specimens.

5 -Basal texture is not suitable starting texture for rolling of HCP materials.
6 -Twinning in the rolled specimens proves that there were not 5 perfect slip systems even after 4 passes ECAP.

References

[1] G.E. Dieter, Mechanical Metallurgy, McGraw-Hill Book Company, 1988, pp. 189–191. SI metric edition.
[2] R.Z. Valiev, T.G. Langdon, Prog. Mater. Sci. 51 (2006) 881–981.
[3] M. Rezayat, A. Akbarzadeh, A. Owhadi, Appl. Sci. Mfg. A 43 (2) (2012) 261–267.
[4] M. Rezayat, A. Akbarzadeh, A. Owhadi, Metall. Mater. Trans. A 43 (6) (2012) 2085–2093.
[5] N. Pardis, B. Talebanpour, R. Ebrahimi, S. Zomorodian, Mater. Sci. Eng. A 528 (25–26) (2011) 7537–7540.
[6] Z.C. Duan, X.Z. Liao, M. Kawasaki, R.B. Figueiredo, T.G. Langdon, J. Mater. Sci. 45 (2010) 4621–4630.
[7] R.S. Mishra, Z.Y. Ma, Mater. Sci. Eng. R 50 (2005) 1–78.
[8] Y. Iwahashi, J. Wang, Z. Horita, M. Nemoto, T.G. Langdon, Scr. Mater. 35 (1996) 143–146.

[9] M. Kamachi, M. Furukawa, Z. Horita, T.G. Langdon, Mater. Sci. Eng. A 361 (2003) 258−266.
[10] R.Z. Valiev, R.K. Islamgaliev, I.V. Alexandrov, Prog. Mater. Sci. 45 (2000) 103−189.
[11] V.M. Segal, Mater. Sci. Eng. A 476 (2008) 178−185.
[12] ASM Metals Handbook, vol. 2, ASM International, 2005, pp. 1424−1589.
[13] S.M. Masoudpanah, R. Mahmudi, Mater. Des. 31 (2010) 3512−3517.
[14] N. Balasubramanian, T.G. Langdon, Mater. Sci. Eng. A 410−411 (2005) 476−479.
[15] F.J. Humphreys, M. Hatherly, second ed., Elsevier Ltd, 2004, pp. 282−497.
[16] S.M. Arab, A. Akbarzadeh, J. Magnesium Alloys 1 (2013) 145−149.
[17] S.H. Kang, Y.S. Lee, J.H. Lee, J. Mater. Process. Technol. 201 (2008) 436−440.
[18] S. Li, Comput. Mater. Sci. 46 (2009) 1044−1050.
[19] Y.G. Kim, Y.G. Ko, D.H. Shin, S. Lee, Acta Mater. 58 (2010) 2545−2554.
[20] H.K. Lin, J.C. Huang, T.G. Langdon, Mater. Sci. Eng. A 402 (2005) 250−257.
[21] S. Suwas, G. Gottstein, R. Kumar, Mater. Sci. Eng. A 471 (2007) 1−14.
[22] M.R. Barnett, M.D. Nave, C.J. Bettles, Mater. Sci. Eng. A 386 (2004) 205−211.